Подано результати чисельного аналізу аеродинамічної взаємодії лопатевих вінців осьового компресора у тривимірному потоці ідеального газу. Показано, що основний внесок в нестаціонарні обурювання вносять гармоніки з частотами, які дорівнюють добутку частоти обертання на числа лопаток сусідніх вінців

Ключові слова: тривимірний потік ідеального газу, аеродинамічна взаємодія, чисельний метод

Представлены результаты численного анализа аэродинамического взаимодействия лопаточных венцов осевого компрессора в трехмерном потоке идеального газа. Показано, что основной вклад в нестационарные возмущения вносят гармоники с частотами равными произведению оборотной частоты на числа лопаток соседних венцов

Ключевые слова: трехмерный поток идеального газа, аэродинамическое взаимодействие, численный метод

The numerical analysis results for aerodynamic interaction of the blade rows of axial compressor in 3D ideal gas flow have been presented. There shown that the principal contribution in unsteady disturbance is brought by the harmonics with frequencies which is equal to the product of rotation frequency into the stator blades numbers

Key words: 3D ideal flow, aerodynamic interaction, numerical method

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THE AERODYNAMIC INTERACTION OF THE BLADE ROWS IN THE THREE STAGE COMPARTMENT OF AXIAL COMPRESSOR

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1. Introduction

The numerical analysis of unsteady aerodynamic loads for compressor So3 with taking into account the aerodynamic interaction of 3 stages in 3D ideal gas flow has presented.

The numerical method is based on the solution of the aerodynamic problem for the 3D ideal gas flow through the mutually moving rotor and stator blade rows [1-6].

3D ideal gas flow through the compressor stage with periodicity on the whole annulus is described by unsteady Euler equations in the form of conservation laws, which are integrated with use of the explicit monotonous finite-volume Godunov's difference scheme and hybrid H-H grid.

The algorithm proposed allows to calculate the compressor department with an arbitrary pitch ratio of rotor and stator blades by action of unsteady loads caused of flow nonuniformity.

There shown that the principal contribution in unsteady disturbance is brought by the harmonics with frequencies which is equal to the product of rotation frequency into the stator blades numbers.

1. Problem formulation

Three-dimensional (3D) transonic flow of inviscid nonheat conductive gas through a three stage compartment of axial compressor is considered in the physical domain (Fig.1), including the stator0 (ST0),the rotor wheel 1 (RW1), rotating with constant angular velocity, stator1

(ST1), the rotor wheel 2 (RW2), stator2 (ST2), the rotor wheel 3 (RW3), stator3 (ST3).

The meridional sections of compressor has been shown in Fig 1.

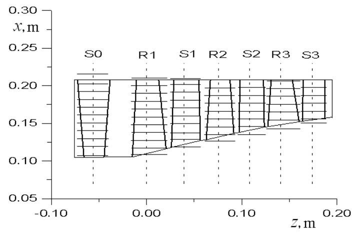


Fig. 1. The calculation domain

Taking into account unperiodicity of flow in circumferential direction the calculated domain includes all the rotor and stator blades. The calculated domain divides on seven subdomains having the common intersection in an axial gap. In each of subdomains the geometric and aerodynamic characteristics of rotor and stator are written in relative or absolute coordinate system rigidly fixed with rotating rotor wheel or stator blade respectively.

In which time moment the flow structure is characterized with periodicity on minimal angular step.

$$T_{min} = \frac{2\pi\,(k_{S0}+k_{R1}+k_{S1}+k_{R2}+k_{S2}+k_{R3}+k_{S3})}{(z_{S0}+z_{R1}+z_{S1}+z_{R2}+z_{S2}+z_{R3}+z_{S3})},$$

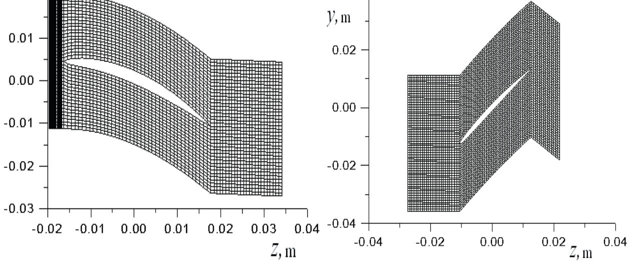
where z_{Ri} and z_{Si} are the rotor and stator blades numbers, k_{Si} and k_{Ri} are mutually simple numbers which are proportional to z_{Ri} and z_{Si}.

In this case the calculated domain has the angular step T_{min} and includes k_{S0} interblade passages of stator 0, k_{R1} interblade passages of rotor 1, . k_{S1} interblade passages of stator 1, k_{R2} interblade passages of rotor 2, . k_{S2} interblade passages of stator 2, k_{R3} interblade passages of rotor 3, . k_{S3} interblade passages of stator 3.

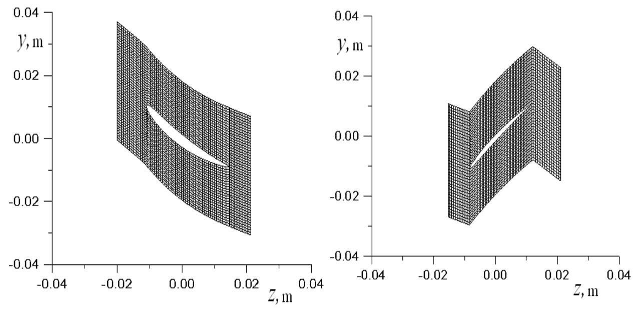
The calculated domain divides on $k_{S0}+k_{R1}+k_{S1}+k_{R2}+k_{S2}+k_{R3}+k_{S3}$ – segments, which of them includes a blade and has extent in circumferential direction equal to rotor blade row step or stator blade row step. In turn each of segments is discretized with use of H-H hybrid grid for rotor passage and H-grid for stator passage.

The tangential grids for peripheral sections of rotor blade and stator blade are shown in Fig. 2 respectively.

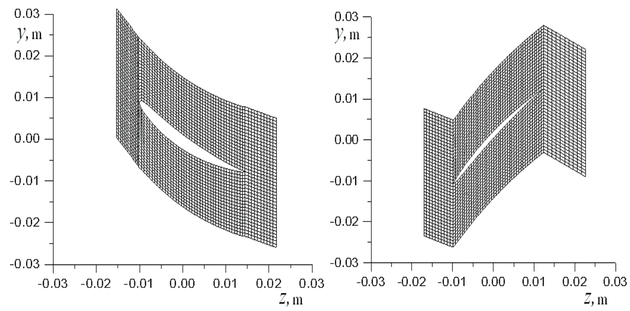
The every grid segment includes correspondently 10*10*84 grid sells for stator 0, 10*60*78 sells for rotor 1, 10*48*64 - for stator 1, 10*40*64 - for rotor 2, . 10*40*62 - for stator 2, 10*40*60 – for rotor 3, .10*30*60 – for stator 3.



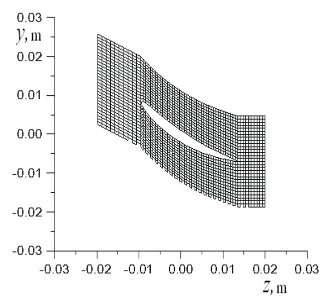
a) b)



c d)



e) f)



g)

Fig. 2. The tangential grid for rotors and stators
a) — ST0; b) — Rotor1; c) — ST1; d) — Rotor2; e) — ST2; f) — Rotor3; g) — ST3

The equations for the spatial transonic flow, including in general case strong discontinuities in the form of shock waves and wakes behind the exit edges of blades, are written in the relative Cartesians coordinate system rotating with constant angular velocity ω, according to the full non-stationary Euler equations, presented in the form of integral conservation laws of mass, impulse and energy [1, 7]:

$$\frac{\partial}{\partial t}\int_{\Omega} f\,d\Omega + \oint_{\sigma} \vec{F}\cdot\vec{n}\,d\sigma + \int_{\Omega} H\,d\Omega = 0\,. \qquad (1)$$

$$f=\begin{bmatrix}\rho\\ \rho\upsilon_1\\ \rho\upsilon_2\\ \rho\upsilon_3\\ E\end{bmatrix};\ \vec{F}=\begin{bmatrix}\rho\vec{\upsilon}\\ \rho\upsilon_1\vec{\upsilon}+\delta_{1i}p\\ \rho\upsilon_2\vec{\upsilon}+\delta_{2i}p\\ \rho\upsilon_3\vec{\upsilon}+\delta_{3i}p\\ (E+p)\vec{\upsilon}\end{bmatrix};\ H=\begin{bmatrix}0\\ \rho a_{e1}-2\rho\omega\upsilon_2\\ \rho a_{e2}+2\rho\omega\upsilon_1\\ 0\\ 0\end{bmatrix};,$$

$$\delta_{ji}=\begin{cases}1 & j=i\\ 0 & j\neq i\end{cases}$$

where f is the symbolic vector of conservative variables; $\vec{F}$ is the inviscid flux through the lateral area σ with normal $\vec{n}$, bounding the finite volume Ω; H is source vector which contains the noninertial terms due to the rotation of the coordinate system.

It is assumed that the unsteady flow fluctuations are due to rotor wheel rotation in nonuniform flow and the flow far upstream and far downstream from the blade row contains at most small perturbations of a uniform free stream. So, the boundary conditions formulation is based on one-dimensional theory of characteristics. The total system of boundary conditions can be represented in the following form [1, 7]:

- before stator

$$T_0 = T_0(x,y),\ p_0 = p_0(x,y),\ \alpha = \alpha(x,y),\ \gamma = \gamma(x,y),$$

$$d\left(\upsilon_3 - \frac{2a}{\chi - 1}\right) = 0;$$

- behind the rotor

$$p = p(x,y);\ dp - a^2 dp = 0;\ d\upsilon_1 - \left(\omega^2 r - 2\omega\upsilon_2\right)dt = 0;$$

$$d\left(\upsilon_3 + \frac{2a}{\chi - 1}\right) = 0.$$

Here $a = \sqrt{\chi(p/\rho)}$ is the sound velocity; T_0 and p_0 are the total temperature and pressure; α and γ are the flow angles in circumferential and meridional directions; χ is the adiabatic coefficient.

On the blade surface moving with velocity w the normal relative velocity is set to zero

$$\vec{\upsilon} \cdot \vec{n} = 0.$$

The discretized form of equations (1) was obtained for an arbitrary moving grid by use of Godunov-Kolgan difference scheme with the 2nd order of accuracy, but in more universal form, extended to three spatial coordinates [8]

$$\frac{1}{2\Delta t}[3f^{n+1}\Omega^{n+1} - 4f_n\Omega_n + f_{n-1}\Omega_{n-1}] + \left[(F_1\sigma)_{i+1} - (F_1\sigma)_i\right] +$$
$$\left[(F_2\sigma)_{j+1} - (F_2\sigma)_j\right] +$$
$$+\left[(F_3\sigma)_{k+1} - (F_3\sigma)_k\right] + H_n\Omega_n = 0. \qquad (2)$$

Here F_1, F_2, F_3 are inviscid flux vectors (F_1, F_2, F_3)= $\vec{F}\cdot\vec{n}$; subscripts and superscripts correspond to previous and next time iterations. The gasdynamic parameters on the lateral sides (expressions in square brackets) are defined by the solving of the problem about the break-down of an arbitrary discontinuity on the moving interfaces between two adjacent cells (Rieman problem) by using a piecewise linear approximation of parameters in grid cells.

The time step Δt is constant for all calculated domain and is defined from the stability condition of the difference scheme

$$\Delta t = \frac{\tau_x \cdot \tau_y \cdot \tau_z}{\tau_x \cdot \tau_y + \tau_x \cdot \tau_z + \tau_y \cdot \tau_z},$$

$$\tau_i = \frac{h_{i\,min}}{\max\left((|\vec{\upsilon}_i| + a), (|\vec{\upsilon}_i| - a)\right)},\ i=x,y,z.$$

2. Numerical results

The numerical investigation has been performed for axial compressor, including the nozzle cascade and 3 compressor stages.

The blade rows number ratio is:

$z_{S0} = 42$; $z_{R1} = 28$; $z_{S1} = 35$; $z_{R2} = 42$; $z_{S2} = 42$; $z_{R3} = 42$; $z_{S3} = 56$. So calculated zone of periodicity includes 6 interblade passages of stator 0, 4 interblade passages of rotor 1, 5 interblade passages of stator 1, 6 interblade passages of rotor 2, 6 interblade passages of stator 2, 6 interblade passages of rotor 3 and 8 interblade passages of stator 3.

The rotor rotation speed is 15000 rpm.

The boundary conditions at inlet and outlet have been accepted as follows:

- total pressure in absolute system $p_0 = 101000$ Pa;
- total temperature in absolute system $T_0 = 288$ K;
- flow angles in absolute system in radial and circumferential directions are given.

The backpressure at outlet behind stator blade row was given as it has shown in Fig. 3.

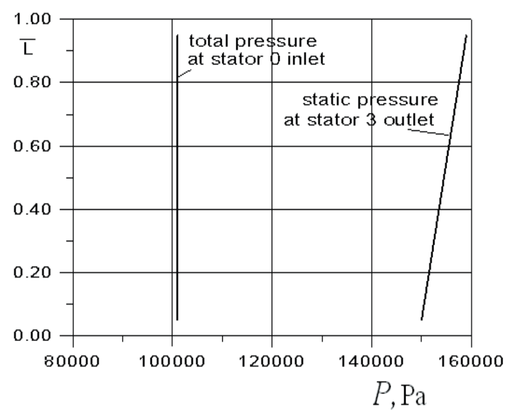


Fig. 3. The total pressure at inlet and backpressure behind stator 3 distribution along the blade length

Below there presented numerical analysis of unsteady aerodynamic loads acting on the rotor blades of 1-3 rotor blade rows for the regime of 15000 rpm. This regime is characterized with mass flow rate of 20.1 kg/sec and pressure increase degree of 2.2.

In Figure 4 there shown the graphs of unsteady loads components (circumferential, axial and moment relatively the gravity center) acting on the blade radial layer for rotor 1 from periphery during the time of a rotor revolution and their amplitude-frequency spectrums.

To process the numerical results obtained it has been used a Fourier transformation of the unsteady time domain solution

$$F(t) = F_0 + \sum_{i=1}^{\infty} F_{1i}\cos(2\pi\nu i t) + F_{2i}\sin(2\pi\nu i t),$$

where $F(t)$ is a physical unsteady load; F_0 is the averaged value of load; F_{1i}, F_{2i} are the Fourier coefficients; i is the harmonic number; ν is the 1st harmonic frequency. In the capacity of ν there chosen the frequency of 250 Hz corresponding to time of a rotor revolution:

the time of rotor revolution is 0.004 sec; the revolution frequency is 250 Hz.

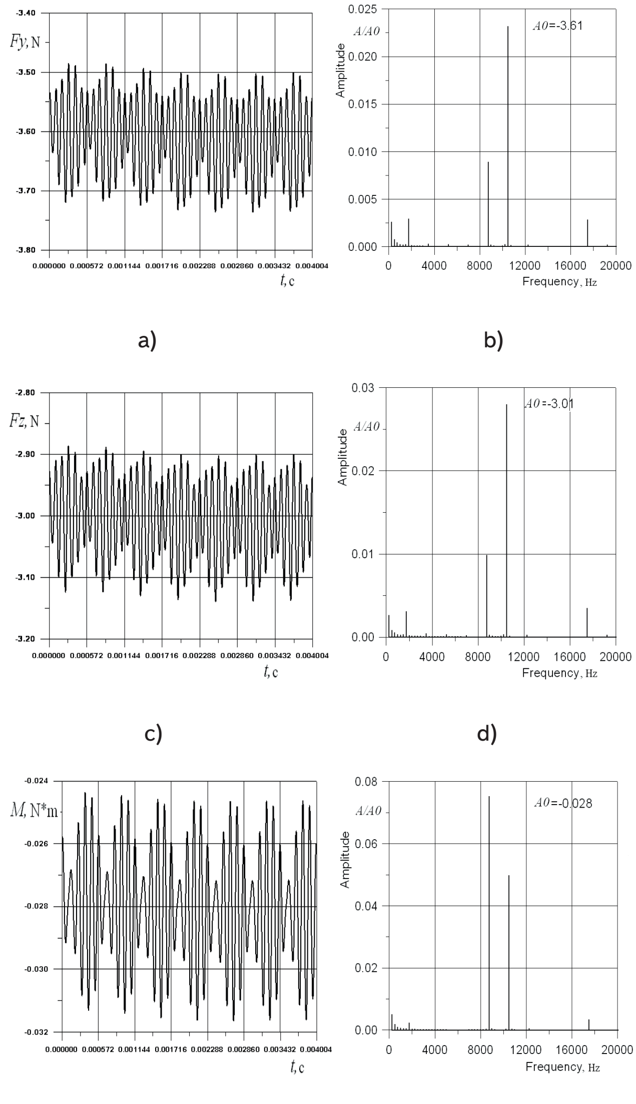


Fig. 4. The aerodynamic force acting on the blade of rotor 1 (peripheral layer) a),c),e) –circumferential, axial force and aerodynamic moment change; b),d),f) – amplitude-frequency spectrum

As we can see from graphs the principal contribution to the unsteady components of aerodynamic load acting on blade of rotor 1 is brought by harmonic corresponding to running frequency from stator 1 which is equal to $\nu_{rev} \times z_{S1} = 250 \times 35 = 8750\,\text{Hz}$ (the maximum value in root layer), and by harmonic corresponding to running frequency from stator 0 which is equal to $\nu_{rev} \times z_{S0} = 250 \times 42 = 10500\,\text{Hz}$ (the maximum value in peripheral blade layer). The amplitude of harmonic is equal to 2.5÷3.0% from averaged value for axial and circumferential components, and 10÷40% for aerodynamic moment.

Besides the amplitude-frequency spectrum of unsteady loads includes the harmonic with frequency of 250 Hz (rotation frequency) and 1750 Hz, corresponding to the frequency or periodicity zone.

The maximum values of aerodynamic load for circumferential force takes place at the root layer and decreases to the periphery, but axial force and moment increase from root to periphery.

In Figures 5-6 there presented the unsteady aerodynamic loads acting on the blade of rotor 2 and rotor 3, and their amplitude – frequency spectrum. It should be noted that predominant frequency for unsteady loads for rotor 2 is frequency 8750 Hz, while predominant frequency for rotor 3 is 10500 Hz. It can be explained that the principal contribution to unsteady loads is brought by disturbance which disseminates down the flow from previous stator blade row.

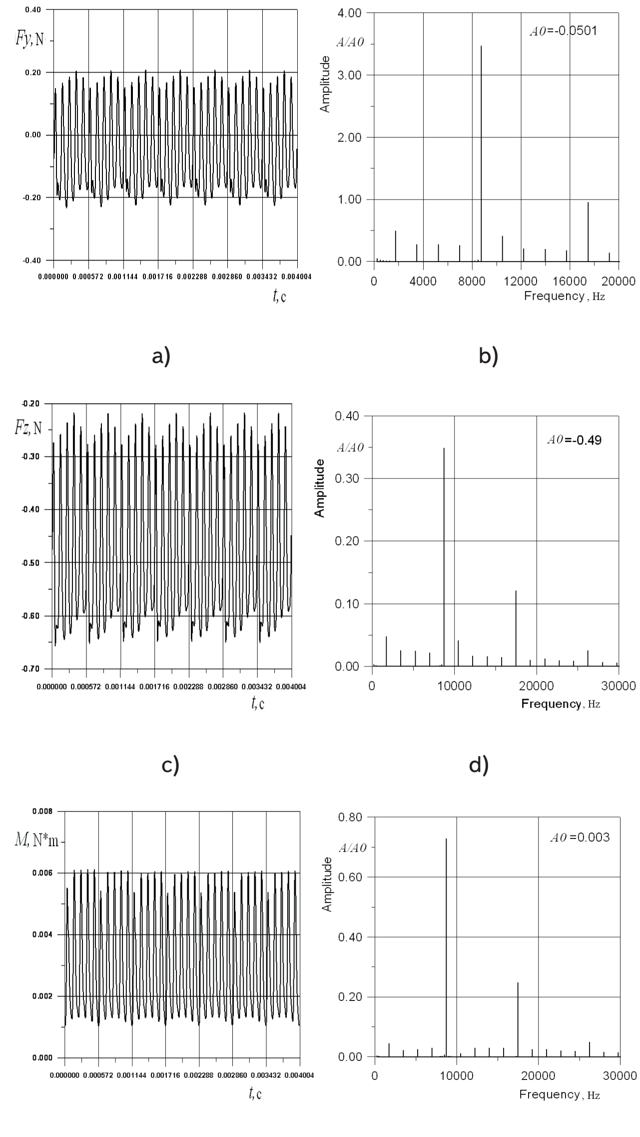
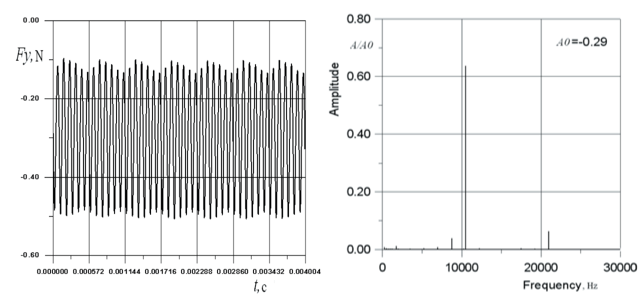
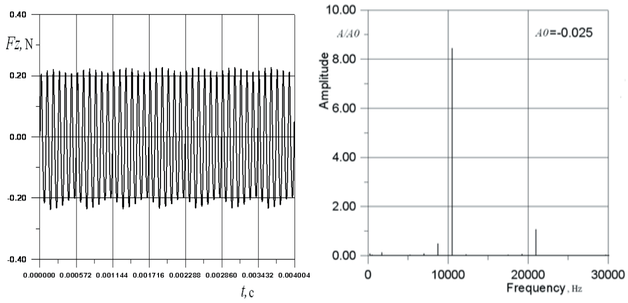


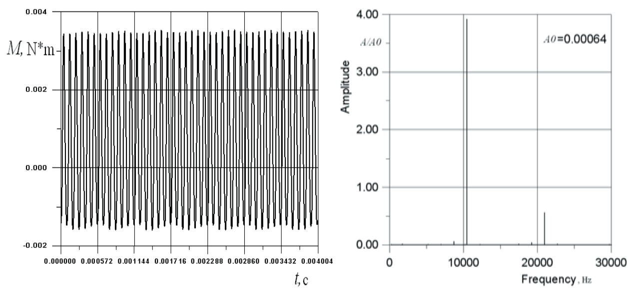
Fig. 5. The aerodynamic force acting on the blade of rotor 2 (peripheral layer): a),c),e) –circumferential, axial force and aerodynamic moment change; b),d),f) – amplitude-frequency spectrum



a) b)



c) d)



e) f)

Fig. 6. The aerodynamic force acting on the blade of rotor 3 (peripheral layer) a),c),e) – circumferential, axial force and aerodynamic moment change; b),d),f) – amplitude-frequency spectrum

Conclusions

The numerical calculations of 3D unsteady ideal gas flow through the compressor stage at n = 15000 rpm has been performed.

There presented the numerical analysis of aerodynamic loads acting on blades.

There shown that the principal contribution in unsteady disturbance is brought by the harmonic corresponding to running frequency which is equal to the product of rotation frequency into the stator blades number.

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